EVALUATION OF ENERGY GENERATION AND GHG EMISSION REDUCTION POTENTIALS THROUGH DIFFERENT SOLID WASTE MANAGEMENT IN NSW

BY:

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Declaration

This research project is submitted in fulfilment of the requirements of the degree of Master of Research, in Macquarie Graduate School of Management, Macquarie University. This represents the original work and contribution of the author.

I hereby certify that this has not been submitted for a higher degree to any other university or institution.

Signed:

Behnam Hosseini Dastjerdi
November 2017

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As a result of this research the following publications have been produced:

1. Dastjerdi, B. H., & Behnia, M. Evaluation of solid waste management policies and their impact on interstate waste transportation in NSW. Paper submitted to the Production and Operations Management Society (POMS) International Conference, Sydney, Australia, December 2017.

2. Dastjerdi, B. H., & Behnia, M. Evaluation of potentials from employing Waste to Energy technologies for Municipal Solid Waste in NSW. Paper submitted to Waste Conference - Coffs Harbour, Australia, 2018.

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ABSTRACT

The ever-increasing global human population as well as the expanding urbanisation and industrialization have resulted in numerous challenges for the environment. Solid waste generation and employing sustainable waste management strategies are the important issues which have become controversial challenges worldwide. Australia is among the countries with the highest rates of waste generation per capita and New South Wales (NSW), with the most population, is responsible for more than one third of whole waste generated in this country. NSW is currently facing serious issues in waste management. The aim of this study was to evaluate energy generation and greenhouse gases (GHG) emission reduction potentials from waste to energy (WtE) technologies in NSW. In addition, waste management policies and legislation in NSW were reviewed and transportation of waste, interstate, as one of their consequences was assessed. The results indicated that, by employing a combination of incineration and anaerobic digestion for landfill waste in NSW, about 50 PJ of energy could be generated; this is equivalent to around 3.4 % of total energy consumption in NSW and the Australian Capital Territory (ACT). Simultaneously, GHG emissions would be reduced by about 900,000 tonnes CO_2 eq. However, Current transportation of waste to Queensland accounts for GHG emissions of about 208 kg CO_2 eq per tonne of waste. These findings show that to efficiently employ WtE strategies, some policies and legislation need reconsideration, like those related to levies, which should be harmonized at a national level. Furthermore, new legislation and incentives should be introduced in order to properly deal with exploiting energy from waste through incineration technology and anaerobic digestion, to keep organic waste out of landfills. Ultimately, strict supervision and rigorous enforcement is needed to ensure that the laws are obeyed.

LIST OF ABBREVIATIONS

ACT	Australian Capital Territory
AD	Anaerobic Digestion
APC	Air Pollution Control
EPR	Extended Producer Responsibility
EPA	Environment Protection Authority
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HHV	Higher Heating Value
IED	Industrial Emissions Directive
IBA	Incinerator Bottom Ash
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LDPE	Low Density Polyethylene
LHV	Lower Heating Value
MCDM	Multi-Criteria Decision Making
NSW	New South Wales
OECD	Organisation for Economic Co-operation and Development
PET	Polyethylene Terephthalate
PP	Polypropylene

PS	Polystyrene
PVC	Polyvinyl Chloride
QLD	Queensland
WID	Waste Incineration Directive
WMAA	Waste Management Association of Australia
WRAP	Waste and Resources Action Programme
WtE	Waste to Energy

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1. INTRODUCTION AND BACKGROUND

Urbanisation and population growth around the world have led to the higher consumption of materials and consequently caused many environmental issues (Hoornweg & Bhada-Tata, 2012; Zaman, 2014). All products have a limited use period which varies from a single use to decades before they are considered as waste (Stammbach, 2017). Solid wastes have imposed a significant burden on the environment and become a controversial challenge worldwide. Policies and strategies of waste management are usually defined by governments and therefore, governments should be acting in a way that maximizes the welfare of the inhabitants for which they are responsible. Wastes have the potential to provide renewable energy with a reduction in greenhouse gases (Demirbas, 2008). Therefore, it is logical and necessary to use residual waste with energy content as an energy source and reduce greenhouse gases (GHG). Also, wastes should be recognized as an important potential source of raw materials for industry. In this way, a circular economy could be established, so that the material loops could be closed, as well as reducing the amount of waste which needs to be landfilled (Turk, Cotic, Mladenovic, & Sajna, 2015).

Waste management has various influences on people: economically, through waste collection fees and taxes; environmentally, through emissions to air and indirect system effects like contamination of underground water resources and soil; as well as human health effects such as the psychological impact of the location of landfills or other facilities (Reich, 2005). The general public has resistance to accept new waste treatments facilities near their residential area, due to concern about adverse effects on the environment and human health. This is related to the fact that waste treatment processes, such as incineration or landfill, cause environmental issues through generating pollution, noise and smell (Giusti, 2009). In choosing the most suitable strategy for waste management, decision-makers need to compare the risk to the environment associated with each waste treatment method.

A large amount of waste is disposed of to landfills, without energy recovery, every year in NSW (Randell, Pickin, & Grant, 2014); and there is no evaluation of energy content or GHG emissions of wastes landfilled in NSW. Moreover, high levies for landfill in NSW have led to transportation of considerable amounts of waste to south east Queensland where, there is no landfill levy (WMAA, 2017).

1.1 Waste Management

Waste management systems consist of various parts: waste generators, waste facility operators and government (decision makers) with considerably different roles and benefits (Martinez-Sanchez, Kromann, & Astrup, 2015). The varied benefits make waste management complicated; however, environmental, economic and social aspects should be considered in waste management. No computer software currently is able to integrate all three aspects of waste management and it cannot be considered fully sustainable (Morrissey & Browne, 2004).

Before 1950 the main disposal method for municipal solid waste (MSW) was open dumping although, the solid waste management, since 1900, has evolved noticeably (Diaz & Warith, 2006). When life is finished as products a new era for those as waste would begin, in other words the grave of products is the cradle of waste. Waste material can be recycled and remain in a cycle of new product manufacturing, transportation, use and finally recycling again to make a closed cycle (Emery, Davies, Griffiths, & Williams, 2007). Energy recovery like generating electricity or heat can increase the benefits of waste management due to governmental incentives and decrease costs such as gate fees (e.g. landfill) (Emery, Davies, Griffiths, & Williams, 2007; Massarutto, de Carli, & Graffi, 2011).

Many criteria such as food habits, cultural traditions, lifestyles, climate and income can affect the composition of MSW (Song, Wang, & Li, 2013). During recent years, plastic packaging consumption has grown remarkably for various reasons, but primarily due to wide usage of plastic in the food industry which was not common in the past. Materials in waste have various market values with those of higher value, such as non-ferrous metals or dense plastics, more favoured by recyclers (Emery et al., 2007).

Waste disposal includes private costs, as well as environmental and social costs. The environmental and social costs can include global warming, contamination of aquifers, risks to human health and loss of amenity for those living near a landfill. Waste management is therefore a significant issue for the community (CIE, 2014).

1.2 Waste Generation and Management: an International Comparison

In 2012 it was estimated by the World Bank that, worldwide, 1.3 billion tonnes of MSW were generated per year and predicted to reach 2.6 billion tonnes per year by 2025 (Hoornweg & Bhada-Tata, 2012). Australia ranked seventh highest for MSW generation among the organisation for Economic Cooperation and Development (OECD) countries per capita basis. Australia’s levels of MSW resource recovery were similar to those in the UK, Finland, Italy and the US, but were significantly below many northern and western EU nations and Korea. These nations make greater use of WtE facilities. Nations such as Switzerland, Austria, Sweden, Denmark, Norway and Belgium dispose of less than 2 % by weight of MSW directly to landfill (Randell et al., 2014).

1.3 Waste Generation and Management in Australia

Greenhouse gas reduction is necessary for many countries. During the Paris UN Climate Conference 2015 Australia committed to reduce emissions by 26–28 % of 2005 levels by 2030 (Department-of-Environment, 2015). In 2010/11, Australians on average generated 2.2 tonnes per capita of waste, 60 % of which was recycled or recovered for embodied energy. In total, Australia generated around 48 million tonnes of waste excluding fly ash (Randell et al., 2014). Australians generated 13.34 million tonnes of MSW in 2015 with a population of 23.78 million. In the same year 5.55 million tonnes of MSW was recycled. The high amount of MSW generation (557 kg per person) marking Australia in 2015 as one of the main MSW per capita producers in the world (OECD, 2017).

Total GHG emissions in Australia in 1998 was estimated at around 460 million tonnes carbon dioxide equivalent (CO_2 eq). The waste sector was known to be responsible for 3.4 % of total GHG generated, with over 90 % of emissions attributed to methane generated by anaerobic decomposition of organic matter in landfills (Pickin, Yuen, & Hennings, 2002).

Table 1 Waste generation and management in Australia (Randell et al., 2014).

	Total		Disposal		Recycling		Energy recovery	
	Millions of tonnes	Energy and material recovery %	Millions of tonnes	Tonnes per capita	Millions of tonnes	Tonnes per capita	Millions of tonnes	Tonnes per capita
ACT	0.93	79	0.20	0.54	0.7	1.93	0.03	0.09
NSW	17.12	65	5.94	0.83	10.7	1.49	0.48	0.07
NT	0.30	9	0.28	1.20	0.01	0.06	0.01	0.06
Qld	7.54	52	3.58	0.80	3.6	0.80	0.36	0.08
SA	3.82	77	0.88	0.54	2.8	1.74	0.14	0.08
TAS	0.65	33	0.41	0.80	0.2	0.31	0.04	0.08
Vic	12.06	62	4.56	0.83	7.2	1.30	0.30	0.05
WA	5.92	39	3.66	1.57	2.1	0.92	0.16	0.07

Australia succeeded in reducing disposal of MSW to landfills by 30 % between 1980 and 2013. But energy recovery has shown the lowest level of increase in the reference period; by less than 10 % and most of this derived from methane capture at landfills (OECD, 2015). The achievements made in the implementation of environmental laws and regulations in Australia such as: National Waste Policy, ACT No Waste Strategy, the NSW Greenhouse Gas Abatement Scheme (GGAS), the National Greenhouse and Energy Reporting System (Act 2007), and the federal Mandatory Renewable Energy Target Legislation, have led to impressive progress in resource recovery over the past decade (Rajaeifar et al., 2017).

Between 2006/2007 and 2010/2011 the amount of waste recycled per capita in Australia increased significantly from around 1.0 tonne to around 1.2 tonnes per capita per year, an increase of around 20 % in four years. In NSW this growth was around 28 %. Data in Randell et al. (2014) demonstrated that in the same period, NSW increased waste generation by 7%, but managed to reduce disposal by 19 % which was the highest rate among all jurisdictions.

Moreover, energy and material recovery rates rose by 31 % and 20 % respectively (Randell et al., 2014).

1.4 Waste Generation and Management in New South Wales

Waste data are often difficult and expensive to collect, and the requirements, scope and mechanisms for collection and reporting differ throughout Australia. When there are no precise data, the authors are forced to make estimates based on uncertain or sparse data, so the reliability of the results varies. Fortunately there are waste data, with high reliability, in NSW (Randell et al., 2014).

In 2010-11 NSW households, businesses and government generated around 17.1 million tonnes of waste (CIE, 2014). Waste generation per capita for NSW was around 2.39 tonnes per year and 6.55 kg per day which is considerably high compare to average amount. Municipal solid waste (MSW) generation in NSW was about 4.8 million tonnes with a resource recovery rate of 57 %, which is 6 % above the Australian average (Randell et al., 2014). The maximum capacity of advanced waste treatment in NSW is 524,000 tonnes per year, which is just 3 % of generated waste in the state and lack of facilities is the most important barrier to higher resource recovery (Randell et al., 2014).

In 2010-11 NSW commercial and industrial (C&I) waste generation was about 5.5 million tonnes, with a resource recovery rate of 60 %. Construction and demolition (C&D) waste generation was about 6.9 million tonnes, with a resource recovery rate of 75 %, which is 9 % above the Australian average (WMAA, 2017). Nevertheless, there is limited remaining landfill capacity (34.3-36.3 million tonnes) in Sydney, At the current rate of disposal, landfill would not last more than 12 years (Alexandria-Landfill, 2017).

NSW is currently facing serious issues in waste management. Decision makers need to know about environmental consequences of employing different waste treatments. Therefore, the potential energy and emissions of waste materials which went to landfill in NSW was estimated in different scenarios. Moreover, the haulage waste to farther distance cause extra Greenhouse gasses (GHG) emissions. The emissions due to the transportations was estimated with LCA method. The review of waste management policies and regulations of pioneer countries and NSW reveal the important differences between them. The differences will determine main reasons of issues and barriers for sustainable waste management in NSW.

2. LITERATURE REVIEW

There is no optimal system for waste management all over the world, due to differences in waste combination, energy sources, availability of waste treatment options and financial limitations. Therefore, the optimal system for any given region needs to be determined locally to reduce the environmental impact (Mendes, Aramaki, & Hanaki, 2004). Morrissey and Brown (2004) claimed that, in waste management models, is not possible to investigate environmental and economic and social aspects simultaneously through the whole waste management cycle. Landfilling of untreated waste has no social justice, as the landfill gas and leachate problems will be with future generations for hundreds of years (Stammbach, 2017).

2.1 The Concept of Waste Hierarchy

A waste hierarchy prioritizes the treatment of wastes according to their impacts on environment, with waste avoidance the most preferable outcome and landfill the least preferable outcome (WMAA, 2017). This means that if waste avoidance is not possible, reuse of waste items is the most desired approach, then recycling of the materials, recovery of the energy, treatment, and finally disposal to landfill. This concept and sequence has led to higher efficiency in waste management and is widely accepted by waste authorities in different countries. Natural laws, e.g. entropy or the principle that each production process generates undesirable materials as well as desirable materials, prevents waste management from achieving 100 % recycling. Technology can help us to minimise waste, but it will never be reduced to zero (Stammbach, 2017).

The waste sector in NSW has achieved big success to reach a high level of recycling. High landfill levies were used as strong leverage to divert waste from landfills. NSW has the biggest recycling sector among all Australian jurisdictions (WMAA, 2017). In NSW, waste management mainly relies on recycling and landfilling and compared to international standards, it has relatively high recycling rates. However, due to lack of WtE facilities such as incineration power plants, the amount of unwanted material disposed of to landfill is relatively high (SUEZ, 2017; WMAA, 2017).

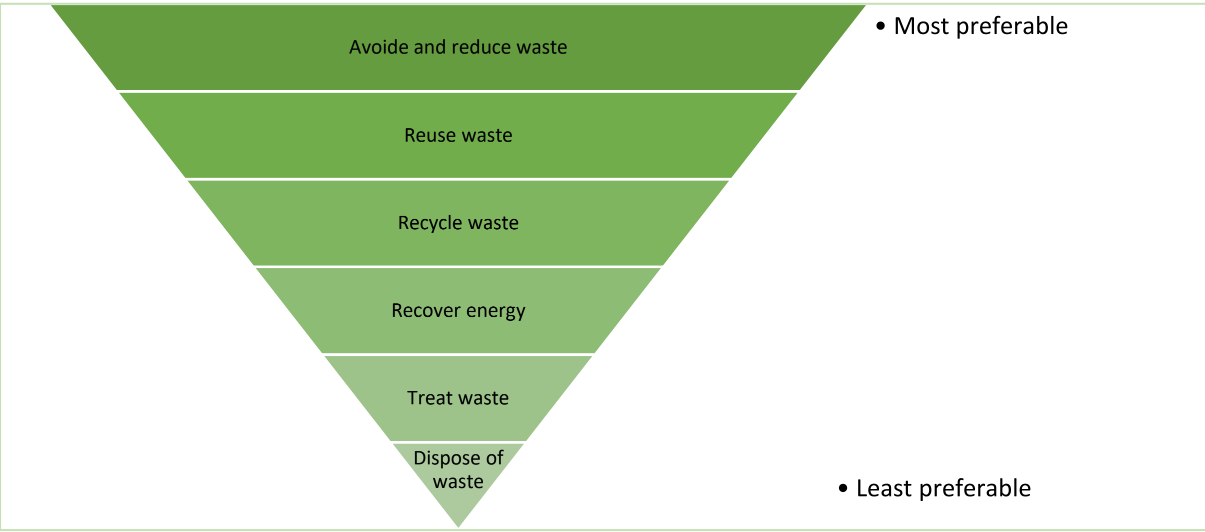

Figure 1 The Waste Avoidance and Resource Recovery Act 2001 in NSW (EPA-NSW, 2017)

The waste hierarchy demonstrates that when further recycling is not feasible, the energy should be recovered before disposal of materials to landfills. Energy recovery should be undertaken in a way that has minimum harm to the environment (WMAA, 2017). Environmental protection needs to incorporate sustainable waste management, where there is no landfilling before resource recovery using the best available and reliable technology (Stammbach, 2017).

All waste cannot be reused or recycled, however, the optimal result of waste management could be achieved just by WtE after material recovery (BCC, 2017). Recycling rates could be increased by recovery of materials, such as metals, from the bottom ash. Recycling has limits, for example, we cannot recycle hygienic products like diapers and recycled products become waste after use. The countries with the highest rate of WtE facilities also have the highest recycling rates. NSW has almost reached the highest possible rate of recycling compared with countries with near zero waste to landfill (Stammbach, 2017).

2.2 Waste Treatment

Nowadays, generating electricity by waste incineration technology is accepted as a reliable waste to energy system. Filtering, by new technologies, reduces the volumes of emission and toxic pollution to very small amounts. Ash remaining from incineration can be used for producing value-added products like bricks for building and construction (Ofori-Boateng, Lee, & Mensah, 2013). The most common form of WtE is Incineration which is an aerobic process (Veolia, 2017). Pyrolysis, like incineration, is a chemical process although it is an anaerobic process. Charcoal has been manufactured by the pyrolysis of wood for centuries. Gasification and pyrolysis have differing procedures. There is no air or oxygen in the pyrolysis process, however, gasification happens in the presence of controlled quantities of air (or oxygen) and steam (WMAA, 2017).

Waste to energy (WtE) is the process of converting waste that is not recycled, into electricity, heat or other energy carriers. WtE facilities can divert up to 95 % of waste from landfill and can play an important role in resource recovery (SUEZ, 2017). The type of waste treatment and the size of facilities are influenced by the amount of waste generated in each area. Large facilities have higher efficiency, but require more feedstock to work efficiently and so could be established in big cities with high population (Mendes et al., 2004).

Biodegradable materials, specifically food waste, can be decomposed by anaerobic digestion methods. Source separated food waste, in controlled industrial processes produce considerable amounts of methane. There are two main kinds of landfills. One without energy recovery and a higher environmental impact, the other with energy recovery and the facilities to capture approximately 50 % of methane emitted from decomposition of biodegradable waste in the landfill. The landfill gas can be used to generate electricity, heat or used as a fuel (Veolia, 2017).

There are three types of WtE system: a landfill gas power plant without an engineered landfill site; a landfill gas power plant with an existing closed engineered landfill site; and a waste incineration power plant. These have been assessed by cost-benefit and sensitivity analysis. The results demonstrate that the average electricity cost from waste incineration is the most sensitive to the variations in annual operating hours; however, the landfill gas power plant with an engineered closed landfill site has the lowest average electricity cost (Holmgren & Amiri, 2007; Roth & Ambs, 2004).

In waste management economic studies, the main approach includes detailed and comprehensive analysis of single technologies, such as incineration, mechanical sorting, etc. On the other hand, there are some studies that include comparative assessment of technologies (e.g. incineration vs. composting; anaerobic digestion vs. landfilling) and consider them as alternative options. This kind of comparison is useful for evaluating the range of application of each technical solution, but it is important to note that these are assessing different technologies which are not capable of treating all components of MSW efficiently (Economopoulos, 2010; Jamasb & Nepal, 2010; Massarutto et al., 2011).

To obtain the best treatment for all the waste stream, it is better to apply a combination of technologies. Anaerobic digestion and incineration together, in comparison with just incineration or landfilling, demonstrate considerably better results in various environmental impacts (Rajaeifar, Tabatabaei, Ghanavati, Khoshnevisan, & Rafiee, 2015).

Pickin et al. (2002) modelled the lifecycle of paper, by evaluating the greenhouse impact of one tonne of paper over its whole lifecycle using various waste management options. It was concluded that landfilling was the worst option and increased greenhouse emission significantly. The results also showed that waste to energy was the most effective treatment (Pickin et al., 2002). As mentioned before, energy recovery from waste paper instead of fossil fuels is a most promising option. Both CO_2 and CH_4 emissions are reduced, providing both long and short-term benefits. Incineration of municipal waste, with energy recovery, is practiced widely overseas is not common in Australia, partly because the incineration method is not accepted in society as reliable and safe for human health (Pickin et al., 2002).

2.2.1 Incineration

A range of WtE technologies including incineration (electricity only or combined heat and power), gasification, pyrolysis and AD can all be applied to waste, however, the most common technology is incineration with electrical energy generation, and will continue to be in the short term (AEA, 2010). The global warming potential (GWP) caused by incineration is largely due to burning plastics, which creates anthropogenic CO_2 emissions. Although burning plastics generate large amounts of GHG, plastics also have a high calorific value and increase the waste's average heating value, making it unnecessary to add fuel to the furnace and so more energy can be recovered from incinerated waste (Mendes et al., 2004). The use of bottom ash to produce pavement bricks is a common approach to reduce the waste stream to landfill (Mendes et al., 2004).

Incineration technology is the main part of the waste management system in many European cities. The incineration plants process residual wastes and recover energy through district heating and or supply electricity to the grid. Those supplying heat to a district are usually located near residential areas such as: Thun, Switzerland (500m from residential housing); Lausanne, Switzerland (2km from the CBD and 100m from residential housing); lssy-les-Moulineaux, France (7km from Paris CBD and 3.6km SW of Eifel Tower); Vienna, Austria (3km from the CBD); and SE London Combined Heat and Power plant, UK (5km from central London) (WMAA, 2017).

Woon and Lo (2016) evaluated two scenarios of electricity generation from an advanced incineration facility (AIF). In the first scenario generation was considerably more than the amount of electricity generated from the landfill extension (LFE) of the second scenario. The higher electricity generation in the first scenario led to 4.7 times more economic benefits compared to the landfill extension option (Woon & Lo, 2016).

Mendes et al. (2004) conducted a study to compare environmental impacts of two disposal methods in Brazil. Although, electricity generated from fossil fuel in this country is limited and comes mostly from renewable sources (Hydropower 94 %), the results showed that incinerating waste instead of landfilling would decrease the overall environmental impact (Mendes et al., 2004).

2.2.2 WtE Facilities Properties

The average capacity of an WtE facility in Europe is around 200,000 tonnes per year, however, the average in North America, is around 370,000 tonnes per year (SUEZ, 2017). Suez estimated that an incineration plant with a capacity of 400,000 tonnes of waste per year would generate a net energy capacity of 38MW. A plant of this size would generate 20MW of renewable baseload power whilst reducing greenhouse gas emissions by approximately 100,000 tonnes a year (SUEZ, 2017).

Veolia estimates the costs of treatment by waste to energy technology, at a plant with the capacity of 200-300 thousand tonnes per year, will range between $ 200 and $ 300 per tonne. The exact cost depends on variables such as landfill levies and subsidies for renewable energy generation (Veolia, 2017). Waste and Resources Action Programme (WRAP) summarised market gate-fees of thermal WtE for Great Britain. Gate fees ranged between $ 130 and $ 234 per tonne depending on the size of the plant. Large scale WtE plant gate fees are even less than a landfill levy, so WtE would be effective in the diversion of waste from landfill (Stammbach, 2017).

Li et al. (2016) analysed the economic aspects of an incineration power plant by the LCC method. It was assumed that 600 tonnes of MSW would be incinerated each day and it would operate 5,500 hours annually for 20 years after being put into production. The gross profit rate was approximately 19%, however, when the annual runtime increases up to 7000 h, the gross profit rate is promoted up to 34.5% (Li, Wang, Zhang, & Ye, 2016).

2.2.3 Waste Management Targets

The Waste Avoidance and Resource Recovery Strategy (WARR strategy) is prepared by the NSW EPA. The last WARR strategy set a key target to increase the waste diverted from landfill from 63 % in 2010–11 to 75 % in 2021–22 (NSW-EPA, 2014). Sustainable waste management strategies are driven by regulatory and standard instruments or financial instruments. They are introduced in different jurisdictions to protect environments (Stammbach, 2017).

2.3 GHG Emissions

Chen and Lo (2016) assessed the greenhouse gas emissions of several municipal solid waste management scenarios in Taiwan. They concluded that heat and electricity generated by WtE could replace an equivalent amount of energy from fossil fuel in Taiwan and mitigate the GHG emissions by around 2 million tonnes CO_2 eq each year (Chen & Lo, 2016). Climate change due to anthropogenic emissions is a well known phenomenon. Every year 86,000,000 tonnes of CO_2 eq are emitted by electricity generation in NSW which is mostly by cheap coal-fired stations. This amount is roughly comparable to the whole of the Philippines, a country with 13 times the population of NSW (Byrne, 2012).

Research was conducted by Mendes et al. (2004) on the environmental impacts of different scenarios of landfilling and incineration; even landfilling with energy recovery had significantly more negative effects on environment than incineration scenarios (Mendes et al., 2004).

In Germany waste incineration plants were an object of hate in the 1980s, as citizens were afraid of dioxin pollution and noise. The number of incineration plants increased and reached 72 in 2007. However, the dioxin pollution in 2007 fell to one thousandth of the amount of 1990 due to the strict pollution control regulation. Combustion of one tonne of residual waste generates about 0.5 tonnes of anthropogenic carbon dioxide (Stammbach, 2017).

Rajaeifar et al. (2017) evaluated electricity generation potentials from MSW in Iran, by three different technologies of incineration, AD, and pyrolysis-gasification. The potentials of electricity generation and the GHG emission reduction potentials were estimated using the LCA approach. They concluded that 5,005.4–5,545.8 GWh of electricity could be generated from MSW annually, which would mitigate GHG emissions around 3.56 – 4.84 million tonnes (0.5 % of total Iranian emissions) (Rajaeifar et al., 2017).

Massarutto et al. (2011) assessed financial benefits of reduction in CO_2 emissions. They adopted the average price of emission trading during 2008–2009, equal to € 19 per tonne. It was assumed that energy recovery from waste displaces oil and coal – powered electricity plants and oil and gas-fuelled domestic heating systems (Massarutto et al., 2011). In an economy with carbon pricing, generating renewable energy from biomass became more beneficial. The anthropogenic CO_2 emissions needs to pay the penalty, however, part of CO_2 emissions from biomass is not anthropogenic (Gibson, Meybodi, & Behnia, 2015).

2.4 Energy Generation

Generally renewable energy systems, such as solar and wind, are affected by environmental conditions and do not generate energy continuously. Thus, they are not appropriate for assisting with peak load time requirements on the grid, however, at WtE facilities electricity generation is steady and continuous (Alexandria-Landfill, 2017).

Table 2 Full load hours annually and Cost of energy technologies (costs in 2009) (Alexandria-Landfill, 2017).

Energy technology	Full load hours p/a	Investment cost (Euros)/MWh
Energy from waste	8,000	~ 30
Wind	1,700	~40
Photovoltaic	800	~ 300

Table 2 demonstrates wind and photovoltaic technologies are able to generate energy for 21 %-10 % of hours in a year that WtE could produce. Based on 1 MWh of energy generated, WtE facilities are more cost-efficient compared to other renewable energy systems. Furthermore, it was concluded that although the initial investment cost of WtE is higher than wind and comparable to solar, the cost per MWh is much lower than other alternative energy sources (Alexandria-Landfill, 2017).

The lower heating value (LHV) required for waste incineration systems to combust without the addition of other fuels is approximately 7 MJ/kg or 1.94MWh/tonne (Weitz, Thorneloe, Nishtala, Yarkosky, & Zannes, 2002). The average LHV of MSW in some jurisdictions like China (4160 kJ/kg) is very low, so to burn in an incinerator they traditionally add other fuel to the MSW to increase the average LHV (Li et al., 2016). In China in order to generate electricity from MSW and alleviate environmental problems, WtE is considered as a solution. In this country, in 2012, around 17×10^6 people with 3,648 kWh/year electricity consumption were using electricity generated from waste incineration power plants (61,775 GWh/year). Although, the energy content of MSW in China is relatively low, a large market and high interest rate made an interesting market for investment in WtE (Li et al., 2016).

Woon and Lo estimated in 2016 that an advanced incineration plant with a capacity of 3000 tonnes/day MSW in Hong Kong could generate 2,280 MWh/day electricity. However, the same amount of MSW in landfill, with a methane gas recovery facility, can only generate 47.1 MWh/day electricity and 564 MWh/day heat. The efficiency of the turbines for landfill gas and incineration were considered 35 % and 19.7 % respectively. An efficiency of 80 % was employed for estimating heat production (Woon & Lo, 2016).

The estimation of GHG emissions in the Defra guideline was conducted by assuming the conversion efficiency of 23 % and based on a lower heating value (AEA, 2010). Thus, direct GHG emissions for one tonne of selected residual waste in power incineration was around 0.42 tonne CO_2 eq. While, the energy required in the process generates 0.04 tonne CO_2 eq emissions and it is estimated that energy exported to the grid offsets around 0.26 tonne CO_2 eq of emissions. The net emission impact is 0.2 tonne CO_2 eq. Recycling metals from the incinerator bottom ash would mitigate emissions by around 0.06 tonne CO_2 eq. (AEA, 2010). Optimised WtE plants are designed for achieving a net electricity generation efficiency of more than 30 % with an advanced water–steam cycle (Gohlke, 2009).

Table 3 Reported electricity efficiency for thermal WtE technologies in studies (AEA, 2010).

Study agency /researcher	Year of study	Kind of Heating Value	Electricity generation efficiency	Citation
(USEPA)	2006	Not clear	17.8 %	(USEPA, 2006)
The European Commission	2001	LHV	15–22 %	(Smith, Brown, Ogilvie, Rushton, & Bates, 2001)
BAT	2006	Not clear	15-30 %	(Prevention, 2006)
C-Tech Innovation	2003	LHV	25.4 %	(Innovation, 2003)
Fichtner	2004	LHV	19-27 %	(Fichtner, 2004)
Defra	2010	LHV	23 %	(AEA, 2010)
European Commission	2017	Not clear	29 %	(COM-34-final, 2017)
Gohlke	2009	LHV	30%	(Gohlke, 2009)

The GHG emissions factor for the National Electricity Market's electricity grid is 820 kg CO_2 eq/MWh (Department-of-Environment, 2016). The amount of GHG emission for coal fired power plant is around 837 kg CO_2 /MWh, however, this factor for electricity generation in a typical WtE plant (40 bar/380 °C) is around 402 kg CO_2 /MWh (Gohlke, 2009).

Lou et al. (2013) estimated heat energy that could be derived from food waste, by anaerobic digestion in NSW, is around 9.88 MJ/kg (Lou, Nair, & Ho, 2013). Dry matter contains energy content, but the, high percentage of moisture in food waste considerably decreases the amount of derivable potential energy. The potential energy generation from food waste in Australia was estimated by the biogas generation potential through anaerobic digestion based on the Matteson and Jenkins (2007) work (Matteson & Jenkins, 2007). In this study which was conducted by Lou et al. (2013) the water content of food waste was not considered, and the results showed that 554.2 GWh electrical energy could be generated (Lou et al., 2013).

2.5 Waste Transportation

There would be no reason for actors in the waste sector to employ reduction measures, and accept emission minimization policies unless they felt the positive effects of GHG emission reductions in the sector (Braschel & Posch, 2013). The GHG emission factor which accounts for waste transportation by 28 tonne articulated trucks was estimated to be 37.5 g CO_2 eq/km tonne (DEFRA, 2011). It is estimated that around 2.4 million tonnes of waste is exported for fuel annually (Total-Environment-Centre, 2017). The commercial benefits in the market determine the destination of waste streams. High levies in the UK increased the cost of waste disposal, consequently it is less expensive to export waste to northern mainland Europe as a fuel for WtE plants. This situation is very similar to sending waste from NSW to QLD (Veolia, 2017). There is no standard definition of waste transportation but we could define it as moving collected waste from a loading point to an unloading point (Braschel & Posch, 2013).

Recycling in NSW is at risk because of interstate waste transportation. This transportation is advantageous, so immediate and effective action is needed to decrease the financial benefit and prevent undermining of the waste sector (Alexandria-Landfill, 2017). The highest landfill levy among Australian jurisdictions is related to NSW, at $ 138 per tonne. A high landfill levy creates a favourable situation for material recovery. Low landfill gate fees due to landfill abundance and no levy, as in QLD, has made it the lowest cost option for disposal of waste from Sydney (Veolia, 2017). But this situation provides insufficient incentive for investment in waste treatment facilities in NSW. The commercial reality is that landfilling waste in QLD is cheaper than in NSW and also much cheaper than recycling (Alexandria-Landfill, 2017).

2.6 Life Cycle Assessment (LCA)

Nowadays, LCA is considered as an environmental management tool. It can be successfully applied to MSW management systems to identify the overall environmental burdens and to evaluate potential environmental impacts (Gibassier, 2017). Researchers evaluating impacts of different technologies, recommend the one with less burden on environment to waste authorities. However, the authorities final decisions will be affected by budget limitation (Martinez-Sanchez et al., 2015). In order to conduct sustainable waste management, first, we need to evaluate waste treatment methods based on their environmental impacts. Life cycle assessment (LCA) is a methodology capable of assessing environmental pollution throughout the life cycle of a specific product and/or service on a cradle to grave basis (Lin, Babbitt, & Trabold, 2013). There are also some social life cycle assessment studies that have presented their results as a single figure, of social costs of waste management options (Liamsanguan & Gheewala, 2008).

LCA was utilized in Defra guidelines to develop the waste management GHG factors. Their evaluation methodology was underpinned by environmental standards like ISO 14040, ISO 14044 and PAS 2050; they also draw on the study conducted in the Netherlands by Sevenster et al. (2007) (AEA, 2010).

Massarutto et al. (2011) conducted a study about material and energy recovery and set the boundaries of the LCA model, from the generation of waste to the point it returns to the productive system (recovery) or to the environment (landfilling) (Massarutto et al., 2011). Assamoi and Laweyshyn (2012) employed the Life Cycle Impact Assessment (LCIA) approach to assess two scenarios. The one was defined as entire waste landfilled, while the other considers that 50 % of the waste was incinerated and the remainder landfilled. The results in Toronto showed that the latter has lower environmental impacts and can reduce greenhouse gas emissions significantly. It also needs less space for waste disposal due to reduction in waste volume (Assamoi & Lawryshyn, 2012). Finnveden and Ekvall (1998) studied LCA as a decision support tool. They concluded, comparing different waste treatments, that if transportation is efficient condition it could be ignored. Transportion was usually not a key issue and had no effect on the environmental issues (Finnveden & Ekvall, 1998).

Hassan et al. (1999) assessed Integrated solid waste models in four Malaysian cities. The models were a combination of current waste management system (landfilling), incineration and composting. Their results showed that incineration had the lowest water emissions and global warming potential among other scenarios, however it cost more than other technologies (Hassan et al., 1999).

In waste management models employing sensitivity analysis is prevalent to evaluate the impact of each parameters (Evangelisti, Lettieri, Borello, & Clift, 2014; Leme et al., 2014; Ofori-Boateng et al., 2013; Reich, 2005). Pratten (1971) 46 years ago modelled Waste management, considering collection, treatment and disposal by engineering cost approaches (Pratten, 1971). Martinez-Sanchez et al. (2015) characterized each cost item in the waste management system by both a technical and an economic parameter. Their cost model was appropriate for the completion of three types of LCC. Conventional LCC, environmental LCC and societal LCC, for socio-economic assessments (Martinez-Sanchez et al., 2015). The gross profit rate of incineration power plants in China was calculated by Li et al. (2016). They claimed that it would be around 19 % although, by increasing the annual runtime from 5,500 to 7,000 hours, the gross profit rate would reach to 34.5 % (Li et al., 2016).

3. REVIEW OF WTE POLICIES AND REGULATIONS

The NSW Environmental Protection Authority (EPA) has recognised the importance of WtE as part of sustainable waste management as acknowledged in Waste Avoidance and Resource Recovery Strategy 2014–21 (NSW-EPA, 2014). The EPA recognizes that the resources recovered by thermal treatment are an integral part of waste management. This has considerable positive potential for both society and environment. WtE is a reliable pathway for treating residual waste when further material recovery through reuse and recycling is not financially sustainable or technically achievable. Part of the energy derived from waste in the WtE process is renewable energy with low carbon emissions and so can make an important contribution to environmental targets.

All strategies, regulations and governmental decisions are translations of policies at lower levels (Helfand & Loomis, 2001). Policies generally involve setting, aims and developing instruments of regulatory (organic landfill bans), economic (landfill levies) and informational/ voluntary (eco labels) (Costa, Massard, & Agarwal, 2010).

3.1 WtE Policies and Regulations – at the International level

Japan has the highest rates of WtE in the world, which are regulated under the Japan Environmental Governing Standards (JEGS). The MSW incineration rate is around 70 % which is exceptional and the emission limits for metropolitan area are stricter than rural areas. Since waste is generated unavoidably and everywhere, all countries are requested to pursue a form of waste management strategy, which is more sustainable. However, national contributions depend on levels of environmental concern, levels of available financial and human resources, available infrastructure, geological conditions, waste characteristics, etc. (Matsuto, 2014). Large amounts of materials with high resource value go to landfills in Australia every year, but unfortunately the regulation, commercial reality, public education and infrastructure is not as advanced as in other OECD countries (Veolia, 2017).

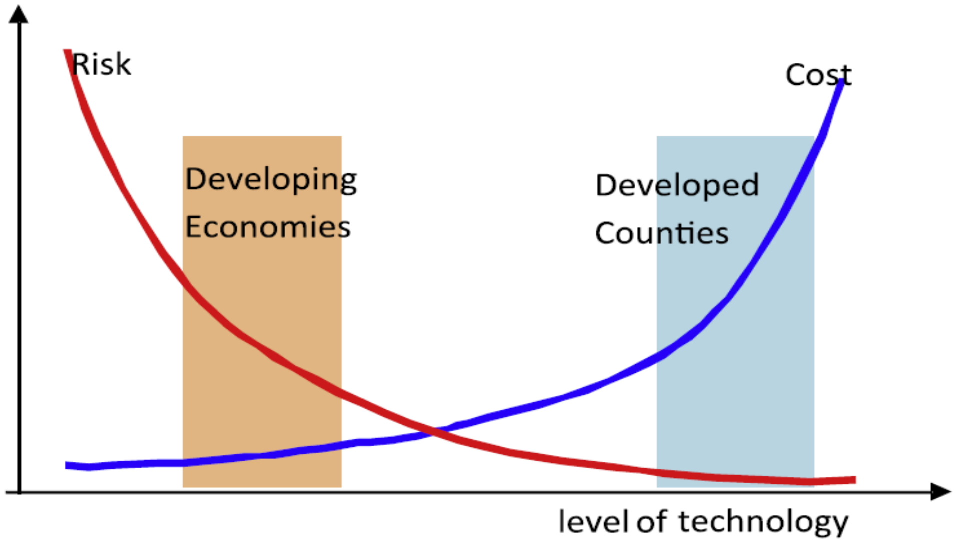

Figure 2 Relationships between levels of risk for environment and human health and cost for different technologies (Matsuto, 2014).

The operation of WtE plants in the USA is regulated under the federal Clean Air Act. This is the comprehensive federal legislation that regulates air emission limits and required pollution controls; it authorizes the Environmental Protection Agency (EPA) to protect public health and public welfare (Veolia, 2017; WMAA, 2017).

The European Union (2006) proposed a hierarchical system of waste management which consists of: first reduction of solid waste production; second, recovery of material; third, recovery of energy; and fourth, landfill disposal (De Feo & Malvano, 2009). It is internationally agreed that the best standards are set and continuously improved from European legislation

(Veolia, 2017; WMAA, 2017). The Waste Incineration Directive (WID) was introduced to determine acceptable limits of emissions, in order to mitigate impacts on the environment as far as practicable (Directive, 2000). It is considered that imposing strict operational and technical requirements can lead to lower pollution in environments and, consequently, lower the risk to human health by thermal WtE emissions. The WID first implemented requirements on incineration in the European Union (EU) and covered a wide range of technical and operational aspects including: types of permitted feed stock, their delivery mechanisms, design of combustion furnaces, abatement plants, residue handling, monitoring equipment and emission limit values. Such technical standards and emission values are also required to be verified through onsite testing/analysis and data reported back to the Environment Agency (WMAA, 2017).

In 2010, the European parliament introduced The Industrial Emissions Directive (IED) and EU countries were called upon to adopt this new regulation (Directive, 2010). This has a chapter about specific provisions for waste incineration plants and waste co-incineration plants. Introduction of the IED caused some changes to the requirements of waste incineration facilities. One of the changes refers to the incineration of waste for electricity generation; it implements new obligatory standards for operation, fuel, technology and emissions to environment.

Incinerator Bottom Ash (IBA) as a residue of the incineration process, needs appropriate management, but IBA management rules are not set in EU directives and it is typically dealt with on a national level. IBA treatment should meet specific environmental regulations to achieve essential permissions and licences for operation. As an example, for installation of an

IBA treatment facility in England or Wales, standards for energy efficiency and efficient use of raw materials should be met (Agency, 2012).

The EU recognizes the WtE process role in a circular economy, provided that waste hierarchy is used as a guiding principle and that WtE does not prevent higher levels of reduction, reuse and recycling. The contribution of WtE in a circular economy (environmentally and economically) depends on how precisely waste hierarchy is followed. Furthermore, it is only by respecting the waste hierarchy that waste-to-energy can minimize GHG emissions, because waste reduction and recycling make larger contributions to energy savings and mitigation of GHG emissions (COM-34-final, 2017).

The concept of Extended Producer Responsibility (EPR) started to become a part of environmental policy in some of countries from the late 1980s. The Organisation for Economic Co-operation and Development (OECD) produced a Guideline to support the development of EPR systems in 2001 (OECD, 2016). EPR is a part of an integrated waste management strategy. It is a policy approach where responsibility of the product producer is extended to the post-consumer stage life cycle (WMAA, 2017).

In the European Union, regulation (EC) No 1013/2006 was introduced to supervise and control transportation of waste (EU, 2006). According to The Basel Convention Ban Amendment, the export of hazardous wastes from OECD countries to non-OECD countries is banned (Sundram, 1997). The shipment of green wastes for recovery within the EU and OECD does not require the consent of the authorities. Despite the Regulation, illegal shipments of waste are still an important problem. It is estimated that the overall non-compliance rate with the regulation could be around 25 %. To strengthen inspection systems in European countries, the Regulation was improved in 2014 through Regulation (EU) No 660/2014 and Member States are required to apply the new changes in 2016/17 (European-Commission, 2017).

Waste management in Denmark and Switzerland, as two pioneer countries, were shaped by increasing tax for incineration and landfill, coupled with a strong landfill ban. When waste incineration with energy recovery and a solid recycling network were established, the governments in these countries imposed landfill bans on all combustible wastes (Costa et al., 2010).

3.2 WtE Policies and Regulations in NSW

The NSW EPA is the most qualified State organisation to set WtE policies and regulations and to be responsible for environmental monitoring WtE facilities; it is better equipped for this responsibility than local government. The NSW EPA is required by law to consider the potential environmental impact across a wider geographic area, under the Protection of Environmental Operations Act (POEO) 1997. It has greater resources to make sure that each facility meets the approval conditions and has technical, policy and legal expertise. The WtE facility data should be available to local councils and each operator should also submit public high level monthly reports about its performance (Randwick, 2017; Stammbach, 2017; Veolia, 2017; WMAA, 2017).

WtE, as part of an integrated waste management strategy, is recognized by the Environment Protection Authority (EPA). It is stated by EPA that, WtE has the potential for the recovery of energy and resources from the thermal processing of waste and it could deliver positive outcomes for the community and the environment. For community acceptance, providing effective information and public consultation about WtE proposals would be necessary. WtE should be employed for residual waste when further material recovery through higher hierarchy waste management option is not financially sustainable or technically achievable; this general condition has been accepted by the community (NSW-EPA, 2015).

3.2.1 Requirement of WTE Facilities

In NSW, WtE guidelines have been developed by the NSW EPA and facilities need to meet the regulatory requirements of the Protection of the Environment Operations Regulation (NSW-government, 2010). The regulation requirements include: emission control and resource recovery; as well as permissions and licences for operating WtE facilities. Similarly, hundreds of operating WtE facilities throughout Europe are strictly controlled by European directives and emission standards. North America and Japan have similar standards and the technologies in use in these regions and Europe are highly developed a reliable. The latest technologies, in terms of environmental impacts and resource recovery, demonstrated better results than those expected by the stringent standards. WtE technology has improved considerably over the last decade and many facilities are operating that incorporate new technology.

A combination of need and legislation generally has driven the development of WtE projects. Unlike Australia, in countries or regions where there is generally a shortage of space for landfill, WtE has been prevalent. Governments in some regions like NSW impose high landfill levies or landfill bans to push waste operators to invest in recycling and energy recovery solutions to divert waste from landfill (Veolia, 2017).

It is necessary to establish WtE project market certainty with appropriate risk allocation, as managing investments in WtE require many important criteria including: appropriate waste levy settings, stable planning and regulatory environments, market demand and committed waste supply, commercial incentives and financing.

WtE facilities require clear processes for permission and construction. Long-term agreements for more than 20 years for waste supply, for at least 70 % of capacity, over that period is critical. These assurances and consistency are considered as key in attracting investment in a new facility and supporting its finance. This could be happened through a supply agreement with a group of councils over the operating life of the facility (Veolia, 2017), although, source separation should be sufficient before residual waste is sent for energy recovery. Furthermore, governments can assist to stimulate investment in this type of long-term infrastructure, through market incentives and landfill levies which make private investment profitable (SUEZ, 2017; WMAA, 2017). However, it would not be profitable without landfill levies, market incentives for WtE and cheap landfill gate fees.

The majority of WtE plants which manage waste in OECD countries have capacities of between 200,000 - 300,000 tonnes per year. One of the current obstacles to diverting waste from landfills to WtE facilities is individual councils. They do not have enough scale to develop a WtE facility of their own. Joint procurement of WtE facilities should be encouraged by the State government. Moreover, the State government could also improve the Local Government Act 1993 to enable councils to increase cooperation (WMAA, 2017). All aspects relating to regulations, approval processes and operation of a WtE facility in NSW are comprehensively covered. (Stammbach, 2017; WMAA, 2017).

Emission generation from WtE processes is strictly regulated in Europe. WtE facilities are equipped with a sophisticated fly ash cleaning and burn waste at high temperatures, in order to meet the European regulation emission limits. Around two thirds of the footprint of a modern WtE facility is related to air pollution control. Exhaust gases are largely steam, oxygen, nitrogen and carbon dioxide (SUEZ, 2017). The European Union's waste incineration directive (WID) aims to minimise the impact on the environment and human health. According to the WID the minimum temperature of 850°C for at least two seconds for municipal solid waste incineration is required. The air emission limits for incineration plant in different jurisdictions are summarised in Table 4.

Except for dioxins the emission criteria are less stringent in NSW than the European Union and the USA (BCC, 2017). The best technology available for WtE facilities could meet European regulation limits therefore it would certainly meet NSW regulation limits.

The NSW Energy from Waste Policy Statement sets emission regulation in a WtE facility: NOx, CO, particles (total), total organic compounds, HCI, HF and SO_2 must be continuously measured. This data must be made available to the EPA in real-time graphical publication, with a weekly summary of continuous monitoring data and emission limit compliance published on the internet. There are also some continuous measurement rules for water steam content of exhaust gas, combustion chamber temperature and concentrations of oxygen. Heavy metals, polycyclic aromatic hydrocarbons, and chlorinated dioxins and furans must be measured at least twice annually (NSW-EPA, 2015). The NSW Energy from Waste Policy Statement draws

Table 4 Summary of emission limits for NSW, EU and the United States (BCC, 2017)

Pollutant	NSW POEO Clean Air Regulation Schedule 3 (Group 6) (One-hour averaging period)	EU Industrial Emissions Directive (IED) (2010/75/EU)				United States Environmental Protection Agency Final Emission Limits for Large Municipal Waste Combustors
		A (100 %) (Half hourly average)	B (97 %) (Half hourly average)	(Daily average)	A (100 %) (Average over a sampling period of a minimum of 30 min average and a maximum of 8 hours)	
Solid particles/Dust/Particulate Matter (mg/m3)	50	30	10	10	NAS*	20
Nitrogen dioxide NO2 (mg/m3)	500 (reported as 350 previously)	400 (for new plants)	200 (for new plants)	200	NAS*	300 (after first year of operation)
TOC (mg/m3)	40 (as VOC)	20	10	10	NAS*	1
Dioxins and furans (ng/m3)	0.1	NAS*	NAS*	NAS*	0.1	13
Hydrogen Chloride HCL (mg/m3)	NAS*	60	10	10	NAS*	37
Cadmium Cd (mg/m3)	0.2	NAS*	NAS*	NAS*	0.05	0.01
Mercury Hg (mg/m3)	0.2	NAS*	NAS*	NAS*	0.05	0.05
Sulphur Dioxide SO2 (mg/m3)	NAS*	200	50	50	NAS*	84
Hydrogen Fluoride HF (mg/m3)	NAS*	4	2	1	NAS*	NAS*
Carbon Monoxide CO (mg/m3)	125	NAS*	NAS*	50	100	NAS*

NAS = No applicable standard*

limitations for the least acceptable energy generation efficiency. A WtE facility must ensure that at least 25 % of the energy recovered from waste is captured as electricity or an equivalent level of heat (NSW-EPA, 2015). Moreover, any heat generated in WTE facilities must be recovered as far as practicable. This can happen more easily in countries with district heating system for heating residential building, however, in NSW this option is not viable.

It is emphasized that energy from waste, to be a valid pathway for residual waste, has to have prior community acceptance. During the approval process it is essential that the proponents provide effective information and public consultation (BCC, 2017). Communications between proponents and governments and early consultation with communities is necessary for a successful WtE project delivery. Noise, traffic, dust and emissions generated by the WtE plant are common reasons for community concern. Modern WtE facilities have sophisticated technology and a holistic plan to manage these concerns (SUEZ, 2017).

3.2.2 Interstate Transportation

Financial instruments like landfill levies are used to divert waste from landfills, however, it would be more efficient if there were no cheaper alternatives for waste disposal. A Carbon market is a positive step towards moving to a cleaner energy situation, but it is the commercial reality that until there is control of waste transportation to QLD, that waste treatment in NSW will be impacted. If the waste transportation to QLD was stopped, the s88 Levy would ensure that resource recovery would improve (Alexandria-Landfill, 2017).

Harmonising the landfill levies throughout Australia seems to be the possible solution for interstate waste transportation. It could provide strong market - based instruments to encourage investment in material recycling as well as WtE. This harmonised levy should be set at a level where landfill gate fee total costs become higher than alternative waste treatments like the £ 80 (about $ 140) per tonne in Great Britain. An appropriate fee will drive waste out of landfills to further composting, recycling and WtE, as demonstrated by countries such as Austria, Belgium, Denmark, Norway, Sweden, and Switzerland which now dispose of less than 2 % by weight of MSW directly to landfill (Stammbach, 2017).

Clause 71 of the Protection of the Environment Operations Waste Regulation (POEO) defined the proximity principle to transportation in the course of business in NSW. There are limitations for the distance that waste can be sent for disposal by motor vehicle. The distance from the source of the waste to disposal must not be more than 150 km. However, it should be noted that where there is no waste disposal facility within 150 km, the regulations permit that waste can lawfully be sent for the disposal to the closest or second closest facility. There is no restriction for interstate waste transportation if the state border is less than 150 km from the source of the waste (NSW-government, 2014).

3.2.3 Energy Generation

The NSW EPA policy was approved regarding energy recovery facilities, in 2015. Due to a decrease in available landfill capacity in the Sydney region the policy was developed and recycling, especially regarding non-putrescible material, was approximately at maximum rates. In the short term, utilizing available technology, recycling could not be much further improved (Alexandria-Landfill, 2017). Obviously kerbside recycling will not be enough for council to accomplish the NSW Government target of 75 % landfill diversion allocated in the NSW Waste and Resource Recovery Strategy 2013-21 (NSW-EPA, 2014). But after source separated recycling, thermal treatment of the residual waste could provide a significant opportunity to increase council's landfill diversion to the NSW Government target and beyond (Randwick, 2017).

The circular economy concept is improving resource security by closing materials loops and extending the lifespan of materials through longer use as well as increasing secondary raw materials use (WMAA, 2017). The waste management industry could offer significant contributions to the circular economy through reuse and recycling as well as WtE. The role of the WtE facility starts after the recycling phase of waste management. Energy generation through the processing of residual waste or WtE is the logical next stage, otherwise residual waste is sent for landfill disposal.

3.2.4 Legal Issues for WTE in NSW

Resource recovery barriers for utilizing WtE, have been established by the current NSW regulations, while there is no limit in its regulatory framework for landfill. Setting no resource recovery restrictions for landfilling means the recognised higher order use (WtE) for waste encounters more regulatory obstacles than landfilling. This could be resolved by adopting equivalent resource recovery criteria for landfilling, or the introduction of landfill bans for waste containing recoverable energy or material such as organic materials or plastics (Stammbach, 2017; WMAA, 2017; WSROC, 2017).

The regulation of residual waste is one of the most important uncertainties inhibiting a realistic solution for WtE. Incinerator Bottom Ash (IBA) and Air Pollution Control (APC) residuals account for approximately 20-25 % and 2-3 %, respectively, of the inputs by weight. Assessing the UK condition, where WtE is an integral part of the waste infrastructure, IBA is permitted for use in construction after further reprocessing, mainly for road construction. However, landfill of IBA is the only current valid choice in Australia and a regulatory framework does not exist presently (Veolia, 2017). The Standard rules SR2012 No13 of the Environmental Permitting Regulations 2010 could be adopted in NSW to licence treatment of Incinerator Bottom Ash (IBA) (Agency, 2012). Today, the re-use of bottom ash is not possible in NSW due to the lack of a Resource Recovery Exemption (Stammbach, 2017). To demonstrate best practice, any WTE proposal in NSW should be required to incorporate a plan for ash processing on site. Consequently, possible reuse opportunities for the ash would be provided and the residual amount sent to landfill would be reduced (BCC, 2017).

3.2.5 Solution for Issues

It is a challenge for the industry to implement policies and regulatory intervention to gain better environmental results. To achieve better outcomes from waste management in NSW, it is necessary to review best practice in environmental regulation in other OECD countries (Veolia, 2017). The resource recovery barriers for C&I waste collections, which practice source separation should be eliminated, otherwise recovery at source could be abandoned in order to achieve the required recovery barriers in a separate recycling operation before WtE treatment (Stammbach, 2017). It has also been recommended that greater support should be given to the renewable energy generation sector; this could happen by increasing a feed-in tariff to provide a consistent and long-term incentive for localised generation (Byrne, 2012).

It has been suggested that the specific limit in the NSW WtE policy for chlorine should be changed. The IED (European standard) applies limitations for hazardous wastes and chlorine concentration in the feedstock should be less than 1 % and in 850 ºC for at least 2 seconds. If hazardous wastes contain chlorine at more than 1 %, then it is more difficult to combust fully and the required temperature would be 1100 ºC (Directive, 2010). The NSW WtE policy applied for waste containing chlorine more than 1 % to waste containing lower chlorine levels. It was demonstrated that waste could be combusted safely with elevated chlorine content and the flue gas could be treated as required by regulations (Stammbach, 2017). It should be noted that, increasing the required temperature to 1,100 ºC would decrease the energy efficiency of the facility (Joyanne, Guy, & Allan, 2015).

The directive 2008/98/EC on waste boost generation of energy means that all new plants in Europe must meet the R1-Regulation, which sets a minimum thermal efficiency for the energy recovery process (Directive, 2008). The aim of the directive was to maximize energy recovery and decrease dependence on energy generated with conventional fossil fuel power plants. According the directive, WtE facilities were required to meet minimum value of 0.60 for existing plants and 0.65 for new plants for R1(Energy Recovery Index) (Branchini, 2015).

Most OECD countries and many emerging economies have introduced Extended Producer Responsibility (EPR) programmes and policies as part of solution for waste management issues. Australia needs to take immediate action in this respect to employ similar programmes and policies (WMAA, 2017). In NSW the waste generator anticipates that the waste will be responsibly treated or disposed of and pays for that service; however, it is usually not important for the Waste Originator what happens to the waste after it leaves his care and control (Alexandria-Landfill, 2017).

4. METHODS AND ANALYSES

In order to estimate energy generation potential of waste flow to landfill in NSW, the latest available data in "The Australian Government's Waste Generation and Resource Recovery" (WGRR) report was used (Randell et al., 2014). Table 5 illustrates the landfilled waste weights in different categories and types. The average values for materials' higher heating values (HHV), moisture fractions and ash fractions were obtained from different resources such as databases, papers and books as referenced. Each waste stream (MSW, C&I and C&D) was classified into 3 classes: combustible, non-combustible, and food waste. These waste data were employed to evaluate energy generation potential and also estimate GHG emissions potential.

Table 5 Waste disposal to landfill data in NSW, 2010/11 (Randell et al., 2014).

Categories	Types	Disposal to landfill (tonnes)				% of total	Per capita per year (g)
		MSW	I&C	C&D	Total		
Masonry materials	Asphalt	0	500	2,500	3,000	0.05	414
	Bricks	32,000	26,500	87,000	145,500	2.45	20,075
	Concrete	0	27,500	253,000	280,500	4.73	38,702
	Rubble	38,000	176,000	221,500	435,500	7.34	60,088
	Plasterboard and cement sheeting	1,500	16,500	29,000	47,000	0.79	6,485
	Sub-total	71,500	247,000	593,000	911,500	15.36	125,764
Metals	Steel	36,000	33,000	35,000	104,000	1.75	14,349
	Aluminium	12,500	5,000	4,000	21,500	0.36	2,966
	Non-ferrous metals (ex. aluminium)	2,500	1,000	500	4,000	0.07	552
	Sub-total	51,000	39,000	39,500	129,500	2.18	17,868
Organic	Food organics	612,012	328,779	0	940,791	15.85	129,805
	Garden organics	298,743	75,819	13,598	388,160	6.54	53,556
	Timber	31,219	249,290	144,157	424,666	7.15	58,593
	Other Organics	5,974	32,430	0	38,404	0.65	5,299
	Biosolids	0	1,927	0	1,927	0.03	266
	Sub-total	947,948	688,245	157,755	1,793,948	30.22	247,520

Paper and cardboard	Cardboard	14,243	50,497	3,021	67,761	1.14	9,349
	Liquid paperboard (LPB)	1,726	0	0	1,726	0.03	238
	Newsprint and magazines	13,811	31,507	1,726	47,044	0.79	6,491
	Office paper	7,769	84,162	4,748	96,679	1.63	13,339
	Sub-total	37,549	166,166	9,495	213,210	3.59	29,418
Plastics	1.Polyethylene terephthalate (PET)	21,000	14,000	1,000	36,000	0.61	4,967
	2.High density polyethylene (HDPE)	20,000	113,500	6,500	140,000	2.36	19,316
	3.Polyvinyl chloride (PVC)	3,000	21,500	1,000	25,500	0.43	3,518
	plastic code 1-3	44,000	149,000	8,500	201,500	3.39	27,802
	plastic code 4-7*	179,500	218,500	12,000	410,000	6.91	56,570
	Sub-total	223,500	367,500	20,500	611,500	10.30	84,372
Glass	Glass	76,000	36,500	3,000	115,500	1.95	15,936
Other	Leather and textiles	73,135	67,542	8,174	148,851	2.51	20,538
	Tyres and other rubber	7,744	20,220	0	27,964	0.47	3,858
	Sub-total	80,879	87,762	8,174	176,815	2.98	24,396
Hazardous	Quarantine	3,000	11,500	0	14,500	0.24	2,001
	Contaminated soil	0	500	504,000	504,500	8.50	69,608
	Industrial waste	95,500	148,000	26,000	269,500	4.54	37,184
	Asbestos	1,000	6,500	191,500	199,000	3.35	27,457
	Sub-total	99,500	166,500	721,500	987,500	16.64	136,250
Other materials reported by jurisdiction		436,000	383,000	177,500	996,500	16.79	137,492
TOTAL		2,023,876	2,181,673	1,730,424	5,935,973	100.00	819,015
%		34.10 %	36.75 %	29.15 %			

*(4. Low density polyethylene (LDPE) 5. Polypropylene (PP) 6. Polystyrene (PS) 7. Other plastics)

4.1 Energy Generation Potential

Two scenarios were defined for evaluation of energy generation potential. In Scenario 1 it was assumed that all classes of material including combustible, non-combustible and food were mixed and incinerated together. However, in Scenario 2 each class of materials was managed with different treatments. Energy was recovered from combustible materials through incineration and from food waste through anaerobic digestion (AD). It was assumed that Non-combustible materials would landfill and due to the fact that they do not contain any biodegradable volatile solids, there was no energy generation potential for this class in landfill.

4.1.1 Incineration

Lower Heating Value (LHV) of wet materials was calculated by equations (1) and (2). Heat energy generation potential through incinerating of waste was calculated by using the equation (3).

(1) $A_w = (1 - f_w) \,.\, A_d$

Where

A_w ash fraction in wet material (dimensionless)

A_d ash fraction in dry material (dimensionless)

f_w water fraction in wet material (dimensionless)

(2) $LHV_{wet} = HHV_{daf} \,.\, \big(1 - (f_w + A_w)\big) - (f_w \,.\, \lambda)$

where

LHV_{wet} lower heating value of material wet material (GJ/tonne)

HHV_{daf} higher heating value of dry and ash free material (GJ/tonne)

λ heat energy is needed to vaporize water at 20°C and equal to 2.45 GJ/tonne (Walter et al., 2000).

(3) $E_h = \sum_{i=1}^{n} LHV_i \,.\, mf_i \,.\, q$

Where

E_h annual available heat energy (GJ/year)

LHV_i lower heating value in wet material type i (GJ/tonne)

mf_i fraction of material type i from total waste amount (dimensionless)

q total amount of waste annually (tonne/year)

The incineration process, with two conversion efficiencies (of 23 % and 30 %) was considered for electricity generation in this study. Equation (4) was used to calculate the amount of electrical energy generation.

(4) $E_e = \frac{1}{3600} \,.\, E_h \,.\, \eta_e$

E_e annual available electrical energy (GWh/year)

η_e generator conversion efficiency (dimensionless)

The lower heating values were considered for energy generation potential for each waste type. Since, a wide range of hazardous wastes were generated in NSW (sludge or liquid-like nature, as well as ash, cinder and slug which are dry in nature), the water content percentage in this category varies between 10 % and 90 %. Carbon content in wet materials also fluctuates in a wide range from 5 % to 50 % (Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006). As a result, LHV for hazardous materials was not predictable, and it was considered that this part of the materials had no energy generation potential; but should be incinerated in order to decrease environmental impact. Also, contaminated soil was considered as non-combustible with no energy generation potential and, for this part of waste, landfill disposal has less environmental impact than incineration.

Table 6 Materials characteristic achieved from resources

Material type	LHV daf MJ/kg	Moisture content (wet) wt %	Ash content (dry) wt %	Ash content (wet) wt %	LHV wet MJ/kg
grass/plant (garden) [a]	18.3	30.34	7.25	-	-
wood [a]	18.88	16.93	2.77	-	-
other organic [a]	19.6	31.35	8.17	-	-
Biomass [a]	17.48	10	38.07	-	-
paper (all) [a]	17.94	7.56	9.99	-	-
1.Polyethylene terephthalate (PET) [a]	22	0	0.7	-	-
2.High density polyethylene (HDPE) [a]	41.15	0.19	0.79	-	-
3.Polyvinyl chloride (PVC) [a]	19.68	0.22	3.28	-	-
4. Low density polyethylene (LDPE) [a]	43.2	0.1	0.3	-	-
5. Polypropylene (PP) [a]	42.94	0.12	0.57	-	-
6. Polystyrene (PS) [a]	41.02	0.11	0.96	-	-
7.Polyethylene (PE) [a]	37.56	0.17	0.03	-	-
Leather [a]	20.01	12.52	5.56	-	-
Rubber & tire [a]	37.65	1.44	14.88		
Food	17[b]	70[d]	-	8.7	1.91[b]
Glass [b]	0	3	-	97	-0.73
Metal [b]	0	6	-	94	-0.147
Inert [b]	0	10	-	90	-0.243
Others materials [c]	11	30.72	23.12	-	-

(Phyllis, 2017)[a] ; (Rand, Haukohl, & Marxen, 2000)[b] ; (ISWA, 2013)[c] ; (AEA, 2010)[d]

4.1.2 Anaerobic Digestion (AD)

NSW generates approximately 1,411,500 tonnes of food waste per year, of which, around two thirds (940,791 tonnes) was landfilled. Typically the food waste, with high moisture content, has a relatively low LHV. Therefore, food waste treated through AD, could generate higher amounts of energy compared to incineration. It was assumed in this study that food waste comprised 70 % moisture and 30 % dry matter (Bingemer & Crutzen, 1987). Methane (CH_4) generation of $98m^3$ per tonne of food waste was considered realistic, according to WRAP calculations. The lower heating value of 35.8 MJ/m^3 was utilized in calculation for methane (Zaher et al., 2010). The Defra guideline was followed in this part to calculate energy generation potential (AEA, 2010). It has been assumed that 3 % of generated methane would escape and methane would be converted to electricity at a conversion efficiency of 37 % while 15 % of this amount would be fed back into the process (AEA, 2010).

The equation (5) below was employed for calculation of heat energy from AD process in this study.

$$E_{hAD} = q_f \,.\, b \,.\, Q_{CH4} \,.\, (1 - s)$$

Where

E_h annual available heat energy from AD process (GJ/ year)

q_f total amount of food waste annually (tonne/ year)

Q_{CH4} volumetric heating value of CH_4 (GJ/m^3)

b CH_4 yield (m^3/tonne)

s fraction of CH_4 escape (dimensionless)

Also, the electrical energy from the AD process was calculated by equation (6).

$$(6)\ E_{eAD} = \frac{1}{3600} \cdot E_{hAD} \cdot \eta_{ADe}$$

E_{eAD} annual available electrical energy from AD process (GWh/ year)

η_{ADe} engine generator efficiency of CH_4 (dimensionless)

In Scenario 2, food waste was treated by AD technology and 31.45 % was utilized in the calculation for electricity generation efficiency (η_{ADe})

4.2 Emissions Reduction Potential

Emissions reduction potentials were estimated for three scenarios. In this section, a baseline scenario was added to the two other scenarios, which were described in section 4.2. The baseline scenario assumed that all waste classes were landfilled - as was happening in reality.

The emission factors for materials treated by different waste management options in NSW were not available for this study, so net emissions from materials for different treatments in the Defra guidelines (data collated and developed by WRAP 2011) was employed (AEA, 2010). The IPCC method (Eggleston et al., 2006) was followed for quantifying the GHG emission related to a specific material and waste management. The biogenic carbon was not considered as GHG emissions and also the impacts of the waste treatment process were offset by avoiding the requirement to generate electrical energy from primary fuelled plant. Therefore, the electricity generation efficiency in incineration and the AD process directly affects the amount of GHG reduction. In scenarios 1 and 2, for estimation of GHG emissions from incineration technology, the electricity generation efficiency of 23 % on LHV of waste and for AD technology 31.45 % on LHV of generated methane was utilized. Moreover, the residue material in the AD process was assumed to be used in agriculture, instead of fertiliser. This means it could have a larger GHG emission reduction potential due to avoiding the need for fertilizer generation.

Table 7 shows the net emissions from different kinds of materials through waste to energy technologies and landfill disposal. The negative amount for material-technology means the anthropogenic emissions from specific material in a specific process is less than the emissions that were offset by energy or new material generation.

The emissions of waste in landfill was estimated by assuming that the landfills were equipped with methane capture facilities. In landfill, the process of decomposition of biodegradable materials in anaerobic conditions generates methane. It was assumed by the Defra guideline that 75 % of generated methane in landfill was captured, from this amount 46 % was utilized for electricity generation, at an electricity generation efficiency of 35 %. Also, it was assumed that 10 % of uncaptured methane would be oxidised before escaping to the atmosphere (AEA, 2010). Due to landfill restrictions since 2006 for liquid wastes and tires in the UK, there were no data about GHG emission from tyres in landfill (Costa et al., 2010). Therefore, GHG emissions from tyres were not included in the total emissions result in the baseline scenario.

Table 7 Net emissions from materials for different treatment (AEA, 2010)

Material type	kg CO_2 eq emitted per tonne of waste treatment		
	Waste to Energy		Landfill
	Incineration	Anaerobic Digestion	
Paper and Cardboard	-529		580
Food waste	-89	-162	450
Garden/plant waste	-63		213
Other organic	-271		230
Wood	-817		729
Textiles	600		300
1.Polyethylene terephthalate (PET)	1,833		34
2.High density polyethylene (HDPE)	1,057		34
3.Polyvinyl chloride (PVC)	1,833		34
plastic code 4-7	1,057		34
Ferrous metal	31		21
aluminium	31		21
other metal	29		20
Aggregate materials	35		10
Glass	26		26
Tyres	-1,500		
Estimated impact of other materials	97		81

Equation (7) was used to calculate the amount of GHG emissions in each scenario annually.

$$(7)\quad C_e = \sum_{i=1}^{n} cf_{ij} \,.\, mf_i \,.\, q$$

Where

C_e annual net GHG emissions (CO_2 eq tonne/ year)

cf_{ij} life cycle conversion factors for material type i and treatment j (CO_2 eq tonne/tonne)

mf_i fraction of material type i from total waste amount (dimensionless)

q total amount of waste annually (tonne/ year)

All calculations in sections 4.1 and 4.2 was done by excel Microsoft Office 2016.

4.3 Waste Transportation Emission

The aim of this section was evaluation of GHG emissions for two different waste transportation routes to make a comparison between their impacts. As discussed in section 3.2.2, in NSW the distance from the source of the waste to the disposal facility must not be more than 150 km. Therefore, this was considered as maximum legally approved distance for waste transportation. However, the distance (930 km) from Sydney (NSW) as a waste source to south eastern QLD as a destination, was considered as the second waste transportation distance.

In 2015–16, landfill operators in Queensland received 566,000 tonnes of waste from interstate sources, a 213,000 tonne increase from the 353,000 tonnes reported in 2014–15. The transported waste included around 50,000 tonnes of MSW and C&I waste and 494,000 tonnes of C&D waste. The C&D waste was almost double the amount reported in 2014–15 (EHP-Queensland, 2016). The distance from Sydney in NSW as the waste generation source to Brisbane (921 km) or Ipswich (940 km) in south eastern QLD as destination was obtained as shortest road distance from google maps. It was assumed that waste transportation distance would be 930 km and transportation was done one way by full trucks (28 tonnes each). The emissions of the trucks on the return trip were excluded from the scope of evaluation in this section.

As a calculation tool, SimaPro software version 8.4 was used to carry out the LCA. In order to find the environmental impact, the Ecoinvent database v3.4 was used. The Inventory tables of the data base which was used in this section include construction of the infrastructure (roads, bridges and tunnels), manufacturing of trucks, direct energy and working material consumption and emissions during operation. Also, end of life and production waste were included.

5. RESULTS AND DISCUSSION

The results of this study are divided into three parts: energy generation potential from landfilled waste was assessed for two different scenarios in NSW; global warming potentials were estimated for three waste management scenarios; and finally GHG emissions of two different waste transportations as a consequence of difference in policies and regulations related to landfill levies in NSW and QLD.

5.1 Energy Generation Potential

Waste to energy (WtE) offers an alternative waste management for landfilled waste in NSW. In this section, two scenarios were assessed, in scenario 1 it was assumed that the waste flow was not separated. Therefore, all three classes (combustible, food and non-combustible) of each waste stream were incinerated together. However, in scenario 2 it was assumed that combustible, non-combustible and food waste would be treated separately. Combustible waste would be treated through incineration, waste food would be treated through AD and non-combustible waste was landfilled. Energy generation for each waste class for both scenarios were calculated.

5.1.1 Scenario 1 (Incineration)

The composition of materials in waste streams determine their energy content. The moisture and ash content in each material was determined in order to calculate the exploitable energy. Lower Heating Value (LHV) of materials in all three waste streams were calculated. The calculation methods, which were explained earlier in the Section 4.2.1, were employed to calculate energy generation potential through incineration. Lower heating value (LHV) and ash content in natural condition (wet condition) was calculated and the results can be seen in Table 8. The highest LHV among all materials was related to the plastics and among organic materials wood. LHV of waste materials were in inverse relation to their ash and moisture contents.

Table 8 Ash content and lower heating value in wet materials

Material type	Ash content (wet) wt %	Lower Heating Value (LHV) (wet) MJ/kg
Grass/Plant (garden)	5.05	11.08
Wood	2.30	14.83
Other organic	5.61	11.59
Biomass	34.26	9.50
Paper (all)	9.23	14.74
1.Polyethylene terephthalate (PET)	0.70	21.85
2.High density polyethylene (HDPE)	0.79	40.74
3.Polyvinyl chloride (PVC)	3.27	18.99
4. Low density polyethylene (LDPE)	0.30	43.02
5. Polypropylene (PP)	0.57	42.64
6. Polystyrene (PS)	0.96	40.58
7.Polyethylene (PE)	0.03	37.48
Leather & Textile	4.86	16.22
Rubber & tire	14.67	31.55
Other materials	16.02	5.11

Municipal solid waste (MSW) stream contained valuable material and energy contents. As Table 9 shows around 2,023,876 tonnes of MSW was landfilled in NSW (2010/2011). Food waste comprise 30.24 % of this MSW. However, due to high moisture content it has relatively low LHV of 1.91 MJ/kg. Plastics have the highest LHV among all different types of waste and could generate roughly 8,677.6 TJ of heat energy which is around 51 % of total net energy of combustible waste. Non-combustible wastes had negative LHV or net calorific value and these

Table 9 MSW landfilled materials characteristics (weight, percentage, LHV and energy)

Class	Material type	MSW landfilled (tonnes)	% of total	Lower Heating value (LHV) (wet) (MJ/kg)	Net energy in incinerator (GJ)
Non-Combustible	Bricks	32,000	1.58	-0.245	-7,840
	Rubble	38,000	1.88	-0.245	-9,310
	Plasterboard and cement sheeting	1,500	0.07	-0.245	-367.5
	Steel	36,000	1.78	-0.147	-5,292
	Aluminium	12,500	0.62	-0.147	-1837.5
	Non-ferrous metals (ex.aluminium)	2,500	0.12	-0.147	-367.5
	Glass	76,000	3.76	-0.73	-55,480
Food	Food organics	612,012	30.24	1.91	1,168,942.92
Combustible	Garden organics	298,743	14.76	11.8	3,525,167.4
	Timber	31,219	1.54	14.83	462,977.77
	Other Organics	5,974	0.30	11.59	69,238.66
	Paper and cardboard	37,549	1.86	14.74	553,472.26
	1.Polyethylene terephthalate (PET)	21,000	1.04	21.85	458,850
	2.High density polyethylene (HDPE)	20,000	0.99	40.74	814,800
	3.Polyvinyl chloride (PVC)	3,000	0.15	18.99	56,970
	plastic code 4-7	179,500	8.87	40.93	7,346,935
	Leather and textiles	73,135	3.61	16.22	1,186,249.7
	Tyres and other rubber	7,744	0.38	31.55	244,323.2
	Quarantine	3,000	0.15	0	0
	Industrial waste	95,500	4.72	0	0
	Asbestos	1,000	0.05	0	0
	Other materials reported by jurisdiction	436,000	21.54	5.11	2,227,960
TOTAL		2,023,876	100.00		18,035,392
weighted average Net calorific value (LHV) (wet) (MJ/kg)				8.91	

materials just absorbed energy in incinerator and reduced total achievable energy by 80.5 TJ of heat energy.

Commercial and industrial (C&I) landfilled waste contained large amounts of energy. Table 10 illustrates data about the C&I waste stream which was landfilled in NSW. Food waste comprise 15.7 % of total C&I landfilled waste which is half of food waste percentage in MSW. Plastics waste comprise around 16.8 % of total C&I landfilled waste and could generate roughly 14,281.4 TJ of heat energy which is around 56.2 % of total net energy of combustible waste. It should be noted that energy content of plastics waste could not be derived by methane capture technology in facilitated landfills. Non-combustibles in this wastes stream reduced total achievable energy in incinerator by around 92.9 TJ of heat energy.

construction and demolition (C&D) landfilled waste contained very large amount of non-combustible materials and contaminated soil. Table 11 illustrates C&D landfilled waste data in NSW. Approximately two thirds (65.85 %) of C&D landfilled waste was non-combustible materials which could reduce around 153.3 TJ derivable heat energy from incinerator. Timber waste comprised around 8.33 % of total C&D which is highest percentage among all combustible waste in this stream. It could generate around 2,137.8 TJ of heat energy which is approximately 50 % of total net energy of combustible waste. Plastics waste comprises just 1.18 % of total C&D landfilled waste and could generate roughly 796.8 TJ of heat energy which is around 19.3 % of total net energy of combustible waste. There was no food waste in C&D landfilled waste. It should be considered that C&D waste could not be incinerated due to very low LHV and it needs axillary fuel for combustion. Furthermore, incinerating non-combustible material does not generate energy, or increase incineration capacity or increase bottom ash.

Table 10 C&I landfilled materials characteristics (weight, percentage, LHV and energy)

Class	Material type	C&I landfilled (tonnes)	% of total	Lower Heating value (LHV) (wet) (MJ/kg)	Net energy in incinerator (GJ)
Non-Combustible	Asphalt	500	0.02	-0.245	-122.5
	Bricks	26,500	1.21	-0.245	-6,492.5
	Concrete	27,500	1.26	-0.245	-6,737.5
	Rubble	176,000	8.07	-0.245	-43,120
	Plasterboard and cement sheeting	16,500	0.76	-0.245	-4,042.5
	Steel	33,000	1.51	-0.147	-4,851
	Aluminium	5,000	0.23	-0.147	-735
	Non-ferrous metals (ex. aluminium)	1,000	0.05	-0.147	-147
	Glass	36,500	1.67	-0.73	-26,645
	Contaminated soil	500	0.02	0	0
Food	Food organics	328,779	15.07	1.91	627,967.89
Combustible	Garden organics	75,819	3.48	11.8	894,664.2
	Timber	249,290	11.43	14.83	3,696,970.7
	Other Organics	32,430	1.49	11.59	375,863.7
	Biosolids	1,927	0.09	9.5	18,306.5
	Paper and cardboard	166,166	7.62	14.74	2,449,286.84
	1.Polyethylene terephthalate (PET)	14,000	0.64	21.85	305,900
	2.High density polyethylene (HDPE)	113,500	5.20	40.74	4,623,990
	3.Polyvinyl chloride (PVC)	21,500	0.99	18.99	408,285
	plastic code 4-7	218,500	10.02	40.93	8,943,205
	Leather and textiles	67,542	3.10	16.22	1,095,531.24
	Tyres and other rubber	20,220	0.93	31.55	637,941
	Quarantine	11,500	0.53	0	0
	Industrial waste	148,000	6.78	0	0
	Asbestos	6,500	0.30	0	0
	Other materials reported by jurisdiction	383,000	17.56	5.11	1,957,130
TOTAL		2,181,673	100.00		25,942,149.1
weighted average Net calorific value (LHV) (wet) (MJ/kg)				11.89	

Table 11 C&D landfilled materials characteristics (weight, percentage, LHV and energy)

Class	Material type	C&D landfilled (tonnes)	% of total	Lower Heating value (LHV) (wet) (MJ/kg)	Net energy in incinerator (GJ)
Non-Combustible	Asphalt	2,500	0.14	-0.245	-612.5
	Bricks	87,000	5.03	-0.245	-21,315
	Concrete	253,000	14.62	-0.245	-61,985
	Rubble	221,500	12.80	-0.245	-54,267.5
	Plasterboard and cement sheeting	29,000	1.68	-0.245	-7,105
	Steel	35,000	2.02	-0.147	-5,145
	Aluminium	4,000	0.23	-0.147	-588
	Non-ferrous metals (ex. aluminium)	500	0.03	-0.147	-73.5
	Glass	3,000	0.17	-0.73	-2,190
	Contaminated soil	504,000	29.13	0	0
Combustible	Garden organics	13,598	0.79	11.8	160,456.4
	Timber	144,157	8.33	14.83	2,137,848.3
	Paper and cardboard	9,495	0.54	14.74	139,956.3
	1.Polyethylene terephthalate (PET)	1,000	0.06	21.85	21,850
	2.High density polyethylene (HDPE)	6,500	0.37	40.74	264,810
	3.Polyvinyl chloride (PVC)	1,000	0.05	18.99	18,990
	plastic code 4-7	12,000	0.69	40.93	491,160
	Leather and textiles	8,174	0.47	16.22	132,582.28
	Industrial waste	26,000	1.50	0	0
	Asbestos	191,500	11.07	0	0
	Other materials reported by jurisdiction	177,500	10.25	5.11	907,025
TOTAL		1,730,424	100		4,121,396.8
weighted average Net calorific value (LHV) (wet) (MJ/kg)				2.38	

5.1.2 Scenario 2 (Integrated Waste Treatment)

In the scenario 2 the food waste was treated through anaerobic digestion and non-combustible waste was landfilled. It was drawn based on the fact that in most cases incineration of mixed waste materials is not financially beneficial, although technically achievable. In this scenario, combustible waste was incinerated alone which increased the average heating value of incinerator feedstock.

Table 12 Heat energy generation potential from two waste management scenarios

Scenarios	Stream	Class	Treatment	Potential Heat Energy			
				MJ/kg	TJ	GWh	MW
Scenario 1	MSW	All	Incineration	8.91	18,035.39	5,009.83	571.90
	C&I	All	Incineration	11.89	25,942.15	7,206.15	822.62
	C&D	All	Incineration	2.38	4,121.40	1,144.83	130.69
	Total			8.10	48,098.94	13,360.82	1,525.21
Scenario 2 (Integrated treatment)	MSW	Combustible	Incineration	13.97	16,946.94	4,707.48	537.38
		Food	AD	3.40	2,082.77	578.55	66.04
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		9.40	19,029.71	5,286.03	603.43
	C&I	Combustible	Incineration	16.61	25,407.07	7,057.52	805.65
		Food	AD	3.40	1,118.88	310.80	35.48
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		12.16	26,525.96	7,368.32	841.13
	C&D	Combustible	Incineration	7.23	4,274.68	1,187.41	135.55
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		2.47	4,274.68	1,187.41	135.55
	Total			8.39	49,830.35	13,841.76	1,580.11

Moreover, it would decrease the required incineration capacity by around 43.8% (2,601,791 tonnes). However, scenario 2 required anaerobic digestion capacity for 940,791 tonnes food waste. This had the potential to generate around 3,201 TJ of heat energy or 279.7 GWh of electricity from food waste through anaerobic digestion annually in NSW.

Table 13 Electricity generation potential from two waste management scenarios

Scenarios	**Stream**	**Class**	**Treatment**	**Electricity (Incineration Efficiency 23 %)**		**Electricity (Incineration Efficiency 30 %)**	
				GWh	MW	GWh	MW
Scenario 1	MSW	All	Incineration	1,152.26	131.54	1,502.95	171.57
	C&I	All	Incineration	1,657.42	189.20	2,161.85	246.79
	C&D	All	Incineration	263.31	30.06	343.45	39.21
	Total			3,072.99	350.80	4,008.24	457.56
Scenario 2 (Integrated treatment)	MSW	Combustible	Incineration	1,082.72	123.60	1,412.25	161.22
		Food	AD	181.95	20.77	181.95	20.77
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		1,264.67	144.37	1,594.20	181.99
	C&I	Combustible	Incineration	1,623.23	185.30	2,117.26	241.70
		Food	AD	97.75	11.16	97.75	11.16
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		1,720.98	196.46	2,215.00	252.85
	C&D	Combustible	Incineration	273.10	31.18	356.22	40.66
		Non-Combustible	Landfill	0.00	0.00	0.00	0.00
		Sub total		273.10	31.18	356.22	40.66
	Total			3,263.76	372.00	4,165.42	475.51

Table 12 shows heat energy generation potential from waste management scenarios. Scenario 2 generated 1,732 TJ more heat energy than scenario 1 while 1,404 TJ of this difference was related to changing treatment of food waste from incineration to anaerobic digestion. The rest of the difference in energy generation (328 TJ) between the scenarios was related to separation of non-combustible waste from total waste. The landfilled waste in scenario 2 would not generate methane since no biodegradable material remained in this part of waste.

Table 13 shows the electricity generation potentials in scenario 1 and 2; two different conversion efficiencies for electricity generation was considered for both scenarios. GHG emissions estimation in next section was estimated based on incineration with 23 % conversion efficiency. As discussed before incineration as an integrated part of sustainable waste management is now accepted. However, the waste sector is trying to improve the electricity generation efficiency of incineration technology. The highest technology electricity generation efficiency could reach to 30 %. In scenario 2 between 3,263.76 GWh and 4,165.42 GWh electrical energy could be generated.

Incineration of combustible class (3,334,182 tonnes) and treating food waste (940,791 tonnes) through anaerobic digestion could reduce waste flow to landfill considerably. The residue of anaerobic digestion process could be used as fertilizer and only about 25 % of input materials by weight in incineration process remain for landfilling. It means about 833,545 tonnes residual waste remain from both processes. Although, appropriate policies and legislation could minimize landfill capacity requirement by driving waste sector to produce construction material from incineration residual bottom ash.

To conclude, residual waste which was landfilled in NSW could generate between 48,098 TJ and 49,830 TJ heat energy. The amount of achievable energy depends on the level of separation and the technologies employed. NSW and Australian Capital Territory (ACT) consume 1,475 PJ heat energy (Allison et al., 2016). Diversion of combustible waste and food waste from landfills into WtE facilities would provide 3.4 % of total energy consumption.

5.2 GHG Emissions

An evaluation approach was used to compare GHG emissions from three different waste management scenarios. In the baseline waste management scenario, it was assumed that all the classes of waste were landfilled. Similarly, in scenario 1 all classes of waste materials were treated together, but, by incineration treatment. However, in the scenario 2 it was assumed that waste materials of each class of each waste stream were separated, and landfill, incineration and anaerobic digestion treatments were employed for non-combustible, combustible and food waste classes respectively. As can be seen in Table 14, the results indicate that the scenario 2 with 245,425 tonnes CO_2 eq has the lowest net GHG emissions and it was followed by the scenario 1 with 362,671 tonnes CO_2 eq emissions. However, baseline scenario with only landfill disposal has the highest negative environmental impact with 1,153,718 tonnes CO_2 eq emissions. Only treating food waste (940,791 tonnes) by anaerobic digestion in NSW had 575,764 tonnes CO_2 eq the GHG emission reduction potential if the integrated scenario was implemented. The results of evaluation provide a framework for policy makers to compare GHG emissions of different waste management scenarios.

Table 14 illustrates the results of the net GHG emissions based on 1 tonne waste treated through the mentioned scenarios. As can be seen, disposing commercial and industrial waste stream to landfill in baseline scenario generated the highest amount of emissions by around 531,579 CO_2 eq tonnes. However, by employing scenario 2, the amount of emissions could decrease by 406,815 CO_2 eq tonnes. The high amount of organic materials in MSW and C&I led to high

Table 14 Global warming potentials (kg CO_2 eq) of three waste management scenarios

<table>
<tr><th rowspan="2">Scenarios</th><th rowspan="2">Stream</th><th rowspan="2">Class</th><th rowspan="2">Treatment</th><th>Weight</th><th colspan="2">Net Emissions</th></tr>
<tr><th>Tonnes</th><th>Kg CO2 eq /tonne</th><th>Total CO2 eq tonne</th></tr>
<tr><td rowspan="4">Baseline Scenario Landfill</td><td>MSW</td><td>All</td><td>Landfill</td><td>2,023,876</td><td>228</td><td>461,623</td></tr>
<tr><td>C&I</td><td>All</td><td>Landfill</td><td>2,181,673</td><td>244</td><td>531,579</td></tr>
<tr><td>C&D</td><td>All</td><td>Landfill</td><td>1,730,424</td><td>93</td><td>160,515</td></tr>
<tr><td colspan="3">Total</td><td>5,935,973</td><td>194</td><td>1,153,718</td></tr>
<tr><td rowspan="4">Scenario 1 Incineration</td><td>MSW</td><td>All</td><td>Incineration</td><td>2,023,876</td><td>111</td><td>224,848</td></tr>
<tr><td>C&I</td><td>All</td><td>Incineration</td><td>2,181,673</td><td>71</td><td>155,342</td></tr>
<tr><td>C&D</td><td>All</td><td>Incineration</td><td>1,730,424</td><td>-10</td><td>-17,519</td></tr>
<tr><td colspan="3">Total</td><td>5,935,973</td><td>61</td><td>362,671</td></tr>
<tr><td rowspan="12">Scenario 2 (Integrated treatment)</td><td rowspan="4">MSW</td><td>Combustible</td><td>Incineration</td><td>1,213,364</td><td>225</td><td>273,263</td></tr>
<tr><td>Food</td><td>AD</td><td>612,012</td><td>-162</td><td>-99,146</td></tr>
<tr><td>Non-Combustible</td><td>Landfill</td><td>198,500</td><td>19</td><td>3,760</td></tr>
<tr><td colspan="2">Sub total</td><td>2,023,876</td><td>88</td><td>177,876</td></tr>
<tr><td rowspan="4">C&I</td><td>Combustible</td><td>Incineration</td><td>1,529,894</td><td>116</td><td>178,027</td></tr>
<tr><td>Food</td><td>AD</td><td>328,779</td><td>-162</td><td>-53,262</td></tr>
<tr><td>Non-Combustible</td><td>Landfill</td><td>323,000</td><td>13</td><td>4,242</td></tr>
<tr><td colspan="2">Sub total</td><td>2,181,673</td><td>59</td><td>124,764</td></tr>
<tr><td rowspan="3">C&D</td><td>Combustible</td><td>Incineration</td><td>590,924</td><td>-97</td><td>-57,216</td></tr>
<tr><td>Non-Combustible</td><td>Landfill</td><td>1,139,500</td><td>10</td><td>11,877</td></tr>
<tr><td colspan="2">Sub total</td><td>1,730,424</td><td>-26</td><td>-45,339</td></tr>
<tr><td colspan="3">Total</td><td>5,935,973</td><td>41</td><td>245,425</td></tr>
</table>

emissions per tonne from landfill. While, electricity generation of incineration or anaerobic digestion technologies from organic materials could offset large amount of emissions through avoiding emissions of electricity generation by a primary fuelled power plant. Employing incineration for combustible materials in construction and demolition waste stream and anaerobic digestion for food had considerable GHG emission reduction potential. Energy recovery and emission reduction potential of employing WtE comprise strong incentives to use incineration and anaerobic digestion.

5.3 Waste Transportation

Waste management policies and regulations were reviewed in section 3 and one of the issues in NSW which was related to landfill levies regulation was evaluated in this section. The current levies have led to the transportation of a large amount (566,000 tonnes) of waste generated in NSW to south eastern Queensland instead of processing (recycling and energy recovery) or landfilling inside the state. Appropriate policies and regulations are required to ensure incentives and levies push waste stockholders towards the waste management scenarios with less negative consequences. The infrastructure processes and long-term emissions were included in evaluation of global warming potential over a horizon of 100 years.

The results of evaluation indicated that interstate transportation could primarily release a substantial amount of greenhouse gases of 208.5 kg CO_2 eq per tonne (the Table 15) and a total amount of 118,011 tonnes CO_2 eq per year for the amount of waste transported. However, most of the transported waste consist of construction and demolition waste (87.3 %) and it is estimated that this stream of waste emitted around 93 kg CO_2 eq per tonne in landfill. In the scenario B GHG emissions of transportation of waste to the farthest legal distance (150 km)

Table 15 Greenhouse gases emissions of transportation of waste

Substance	Emissions of transportation of 1 tonne waste (kg CO_2 eq)	
	Scenario A	Scenario B
	inside state 150 km	SE QLD 930 km
Carbon dioxide	31.074	192.6588
Methane	1.6125045	9.9975279
Dinitrogen monoxide	0.8341537	5.1717533
Methane, tetrafluoro-, CFC-14	0.0590733	0.3662545
Methane, Bromo trifluoro-, Halon 1301	0.0237762	0.1474124
Ethane, hexafluoro-, HFC-116	0.010989	0.0681318
Methane, dichlorofluoro-, HCFC-21	0.0092574	0.0573959
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	0.005038	0.0312358
Methane, trichloro fluoro-, CFC-11	0.0001035	0.0006414
Methane, tetrachloride-, CFC-10	6.903E-05	0.000428
Methane, dichlorodifluoro-, CFC-12	4.865E-05	0.0003017
Methane, chlorotrifluoro-, CFC-13	4.17E-05	0.0002585
Methane, chlorodifluoro-, HCFC-22	9.319E-06	5.78E-05
Methane, dichloro-, HCC-30	1.293E-07	8.02E-07
Chloroform	6.72E-08	4.17E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	2.243E-14	1.39E-13
Total	33.63	208.50

for each tonne of waste would be approximately 33.63 kg CO_2 eq which is around one sixth of the scenario A. The results in Table 15 and Figure 4 show the significant difference between global warming potential of transportation of waste to these two destinations.

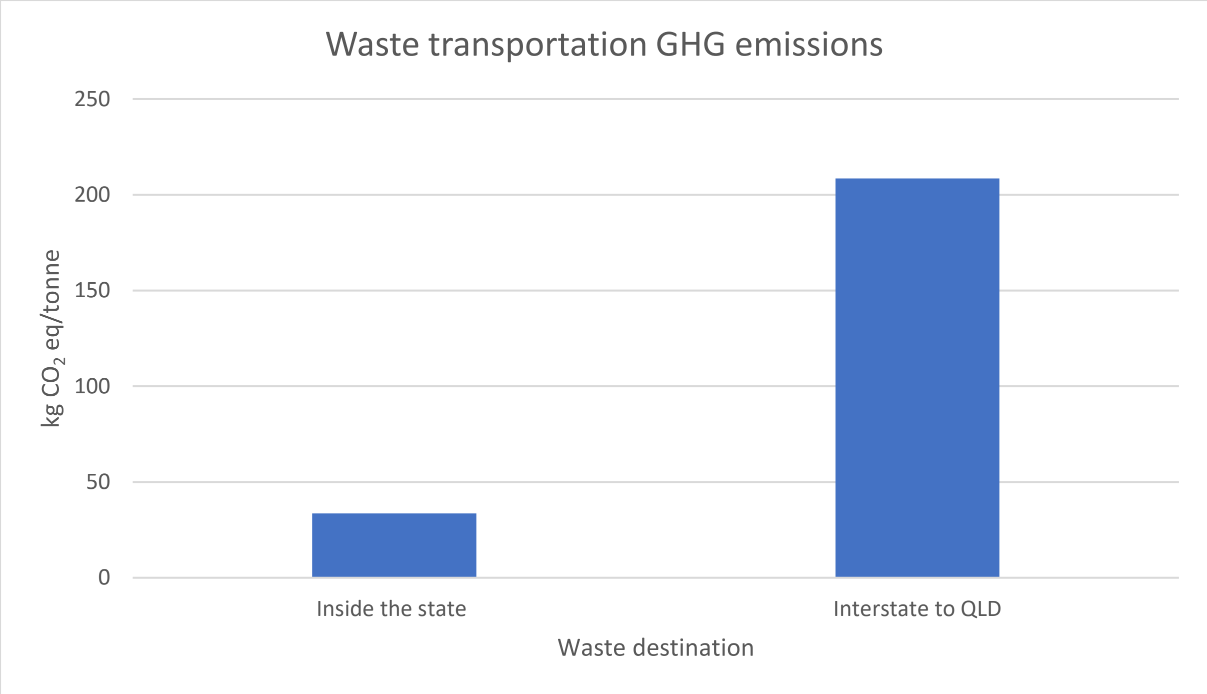

Figure 3 Global warming potential of transportation of one tonne Waste

Therefore, it is suggested to harmonize levies at a national level to prevent transportation of waste to remote places just to avoid landfill levies.

6. CONCLUSIONS

This chapter briefly outlines findings of the study and recommendations for further work. This study offers waste to energy (WtE) technologies as alternative waste treatments for landfilled waste in NSW.

6.1 Summary of Findings

Incineration of combustible parts of the waste in NSW (3,334,182 tonnes) could potentially generate around 46.63 PJ of heat energy or 2979.06 – 3,885.72 GWh electrical energy annually (electricity generation efficiency of 23 % - 30 %). Anaerobic digestion of food waste in landfilled waste (940,791 tonnes) could potentially generate another 3.2 PJ of heat energy or 279.7 GWh electrical energy annually. Diversion of combustible waste and food waste from landfills into WtE facilities would provide 3.4 % of total energy consumption of NSW and Australian Capital Territory (ACT). Furthermore, this could reduce waste flow to landfill by 3,441,427 tonnes per year.

Another outcome of this study, was the evaluation of GHG emissions from three different waste management options for landfilled waste. It provides a framework for policy makers to compare GHG emissions of different waste management treatments. The results indicate that the net GHG emissions from the Scenario 2 with integrated waste management (and all three technologies) (245,425 tonnes CO_2 eq) is lower than Scenario 1 where only incineration treatment (362,671 tonnes CO_2 eq) was used. However, the waste management scenario where only landfill disposal with energy recovery would emit far more greenhouse gases (1,153,718 tonnes CO_2 eq). Simply diverting food waste (940,791 tonnes) from landfill to anaerobic digestion in NSW would have a GHG emissions reduction potential of about 575,764 tonnes CO_2 eq.

Waste management policies and regulations in NSW were reviewed and also the global warming consequences of transportation of waste interstate was evaluated. The current levies have led to the transportation of a large amount (566,000 tonnes) of waste generated in this state to south east Queensland instead of processing (recycling and energy recovery) or landfilling inside NSW. The results indicated that this cheap landfill strategy could release a substantial amount of greenhouse gases of 208.5 kg CO_2 eq per tonne and a total amount of 118,011 tonnes CO_2 eq per year for the amount of waste transported. However, as most of this transported waste comprises construction and demolition waste (87.3 %) and it is estimated that this stream of waste would emit around 93 kg CO_2 eq per tonne in landfill. It means waste transportation to south east Queensland led to around 175 kg CO_2 eq more GHG emissions per tonne of waste which is approximately two times more than GHG emissions from waste in landfill.

In summary, there are financial and technical limitations for reduction, recycling and reuse of waste. However, using WtE in treatment with higher priority would contribute to more sustainable waste management. Energy recovery and GHG emission reduction potentials have demonstrated the necessity of employing incineration and anaerobic digestion technologies in the waste management. This study could be employed as a guideline for decision makers to utilize more sustainable waste management strategy with higher rate of energy generation and simultaneously alleviation of GHG emissions.

6.2 Recommendations for Further Work

Further study is required to evaluate policies and regulations to achieve solutions to reduce barriers or other issues to employ WtE technologies in NSW. Appropriate policies and regulations are required to ensure incentives and levies that push waste stockholders towards a waste management scenario with less negative consequences. New legislation and incentives should be introduced in order to encourage exploitation of energy from waste through incineration technology as well as anaerobic digestion to keep organic waste out of landfills. Levies at a national level should be harmonized and additional waste treatment facilities, as key elements of a sustainable waste management program, should be developed. Emission estimations can be improved by continuous monitoring of GHG emissions from facilities in NSW in future. Further study can be done in future to assess an optimal number of WtE facilities and their locations to minimise waste transportation in the State.

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